

Cores and the Kinematics of Early-Type Galaxies

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ABSTRACT

I have combined the Emsellem et al. ATLAS^{3D} rotation measures of a large sample of early-type galaxies with *HST*-based classifications of their central structure to characterize the rotation velocities of galaxies with cores. “Core galaxies” rotate slowly, while “power-law galaxies” (galaxies that lack cores) rotate rapidly, confirming the analysis of Faber et al. Significantly, the amplitude of rotation sharply discriminates between the two types in the $-19 > M_V > -22$ domain over which the two types coexist. The slow rotation in the small set of core galaxies with $M_V > -20$, in particular, brings them into concordance with the more massive core galaxies. The ATLAS^{3D} “fast-rotating” and “slow-rotating” early-type galaxies are essentially the same as power-law and core galaxies, respectively, or the Kormendy & Bender two families of elliptical galaxies based on rotation, isophote shape, and central structure. The ATLAS^{3D} fast rotators do include roughly half of the core galaxies, but their rotation-amplitudes are always at the lower boundary of that subset. Essentially all core galaxies have ATLAS^{3D} rotation-amplitudes $\lambda_{R_e/2} \leq 0.25$, while all galaxies with $\lambda_{R_e/2} > 0.25$ and figure eccentricity > 0.2 lack cores. Both figure rotation and the central structure of early-type galaxies should be used together to separate systems that appear to have formed from “wet” versus “dry” mergers.

Subject headings: galaxies: nuclei — galaxies: photometry — galaxies: structure

1. The Differences Between Galaxies With and Without Cores

Luminous elliptical galaxies have long been known to have a “core” at their centers, a region interior to which the steeply-rising stellar surface-brightness profile of the envelope

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shallows out to a slowly-rising cusp as $r \rightarrow 0$ (Lauer 1985a; Kormendy 1985a,b). Cores had been predicted to be created when a binary black hole formed in the merger of two pre-existing galaxies ejected stars from the center of the newly formed system (Begelman et al. 1980). This is still the favored theory for their formation.

With the advent of the *Hubble Space Telescope* (*HST*), it became possible to observe the central structure of low-luminosity galaxies that were presumed to have cores too angularly-small to be detected from the ground. These galaxies generally lacked cores, however, instead having steep-cusps in surface brightness as $r \rightarrow 0$ (Lauer et al. 1991, 1992). As larger samples of early-type galaxies were observed with *HST*, a picture emerged in which the most luminous elliptical galaxies were confirmed to have cores, but less luminous galaxies generally did not (Crane et al. 1993; Kormendy et al. 1994; Ferrarese et al. 1994; Lauer et al. 1995). Lauer et al. (1995) called the coreless systems “power-law” galaxies, as they exhibited central light distribution that resembled steep power-laws as the *HST* resolution limit was approached. The differences between these two kinds of systems extend to many more properties than their central structure alone, and in fact define two sub-populations of early-type galaxies that appear to have different formation histories.

1.1. Two Families of Elliptical Galaxies

In parallel with the work on the central structure of early-type galaxies, observations of the dynamics and isophotal structure of elliptical galaxies also motivated the recognition that these systems comprise two distinct groups. The pioneering work of Davies et al. (1983) showed that while “giant” elliptical rotated slowly, less luminous systems were consistent with being rotationally supported. Recent work (Emsellem et al. 2007; Cappellari et al. 2007; Emsellem et al. 2011) continues to show that early-type galaxies are diverse in the degree of organization and amplitude of their rotation patterns.

Early work with CCD cameras showed that elliptical galaxies had isophotes that significantly deviated from perfect ellipses, being either “boxy” or “disky” (Lauer 1985b). Rich investigations into the isophote shapes of large samples of elliptical galaxies showed that galaxies with boxy isophotes correlated with strong radio and X-ray emission, but slow rotation (Bender et al. 1987; Bender 1988; Bender et al. 1989; Nieto & Bender 1989). Galaxies with disky isophotes showed regular rotation patterns, but had little radio or X-ray emission. Nieto et al. (1991) unified the link between central structure and the suite of properties correlated with isophote shape by showing that galaxies with well-resolved cores had boxy isophotes, while those with strongly-peaked profiles had disky isophotes. The ensemble of correlated properties suggested to them that elliptical galaxies might be divided into two

families reflecting different formation histories. Tremblay & Merritt (1996) found marked differences between the typical axial ratios of ellipticals as a function of luminosity, with luminous ellipticals being nearly round, while faint ellipticals were significantly flattened, endorsing the segregation of ellipticals into two families.

Kormendy & Bender (1996) summarized the picture presented by these studies of isophote shape and dynamics of elliptical galaxies, the *HST* surface photometry investigations, and the detailed central structure analysis of Faber et al. (1997) (then in preparation), to argue for an explicit bifurcation of elliptical galaxies into two sequences. One sequence contained the elliptical galaxies with boxy isophotes, cores, and low rotation-amplitudes. The second sequence contained elliptical galaxies with disk-like isophotes, steep central cusps, and rapid rotation.

1.2. Core Structure and the Formation of Early Type Galaxies

Faber et al. (1997) explored the relationships between the physical scale of the cores in the early-type galaxies, extending the ground-based core relationships derived by Lauer (1985a) and Kormendy (1985b), while also testing the link between the form of central structure and other properties of the galaxies noted by Nieto et al. (1991). Faber et al. (1997) demonstrated that core and power-law galaxies were physically distinct subsets of early-type galaxies for more reasons than their nominal differences in central structure. The dominant difference between the two classes is total galaxy luminosity. Most (but not all) early-type galaxies with $M_V > -20$ are power-laws, while most (but not all) early-type galaxies with $-22 > M_V$ have cores. In addition to this, Faber et al. (1997) found core galaxies to rotate slowly, while power-law galaxies rotated rapidly. Core galaxies also had “boxy” isophotes, while power-law galaxies were “disky.” Subsequent work shows that cores are associated with radio-loud active nuclei (Capetti & Balmaverde 2005; Balmaverde & Capetti 2006), and with strong X-ray emission (Pellegrini 2005), results that had been anticipated, given the earlier works that linked radio and X-ray emission to isophote shape.

A crucial finding of Faber et al. (1997) is that rotation and isophote shape discriminate between core and power-law galaxies of the same luminosity. In other words, while the strength of rotation and isophote shape do correlate with galaxy luminosity, as well, the correlations are not perfect and independent information is provided by these parameters. In particular, over the $-22 < M_V < -20$ transition zone in which Power-law and core galaxies coexist, properties secondary to galaxy luminosity still can be used to separate galaxies with the two forms of central structure. In short, the differences between core and power-law galaxies are not simply tied to total galaxy luminosity.

The physical differences between the core and power-law galaxies motivated Faber et al. (1997) to suggest that they were formed by different mechanisms. Power-law galaxies would be formed by the mergers of subsystems possessing significant amounts of gas. During the merger, dissipation would drive gas to the centers of the galaxies, where it would collapse and form stars locally, boosting the central stellar density of the merger remnant. This scenario had been elucidated directly by Mihos & Hernquist (1994). Recent detailed simulations of this scenario strongly resemble the real structure of power-law galaxies (Hopkins et al. 2009). Core galaxies, on the other hand, would be formed by the mergers of systems having little or no gas. The low rotation of core galaxies is a direct reflection of their formation in largely stellar, dissipationless (dry) mergers. As noted at the start of this introduction, Begelman et al. (1980) hypothesized that the cores, themselves, would be generated as the hardening of a black-hole binary formed in the merger would eject stars from the center of the merged system. Simulations of this scenario by Ebisuzaki et al. (1991) and subsequent investigators (Makino & Ebisuzaki 1996; Quinlan 1996) supported this hypothesis. In short, the presence or absence of cores bears witness to how their surrounding galaxies were formed over all.

The division of early-type galaxies into core and power-law groups is identical to their division into two families of elliptical galaxies by Kormendy & Bender (1996) and Kormendy et al. (2009). This latter work, continues to find additional differences between the two sets, extending their dichotomy into differences between the ages of their stellar populations, the α -enhancements of their chemical abundance patterns, and the Sérsic indices of their envelopes. As is discussed in §3, the distribution of the log-slopes of the inner cusps of the core and power-law galaxies is essentially bimodal, making the separation into two groups clear.

The Faber et al. (1997) work was based largely on the relatively small sample of galaxies observed by Lauer et al. (1995), and was also limited by the limited availability of long-slit spectroscopic observations matching the *HST* sample. Subsequent work has greatly expanded the sample of galaxies with both *HST* imaging and high-quality kinematic information. It is now possible to re-investigate the relationship between core structure and galaxy kinematics.

2. The ATLAS^{3D} Rotation Measurements

The ATLAS^{3D} project (Cappellari et al. 2011) used the SAURON IFU spectrograph (Bacon et al. 2001) to obtain high-quality two-dimensional spectroscopy of a large sample of early-type galaxies. In brief, (Cappellari et al. 2011) observed 260 galaxies brighter than $M_{K_S} = -21.5$, within 42 Mpc, constrained by accessible declination and distance from the galactic plane. Emsellem et al. (2011) (Paper III of the ATLAS^{3D} project) used this material

to derive rotation measures,

$$\lambda_{R_{LIM}} \equiv \frac{\int_0^{R_{LIM}} \int_0^{2\pi} F R |V| dR d\theta}{\int_0^{R_{LIM}} \int_0^{2\pi} F R \sqrt{V^2 + \sigma^2} dR d\theta}, \quad (1)$$

where F , is the surface brightness distribution of the galaxy, R is the radius from the center of the galaxy, V is the stellar rotation field, and σ is the stellar velocity dispersion field. In a number of systems, Emsellem et al. (2011) were able to integrate out to $R_{LIM} = R_e$, the effective radius, but for the great bulk of their sample they had coverage only out to $R_e/2$, thus for the remainder of the paper I use their $\lambda_{Re/2}$ parameters to represent the degree to which the galaxies are rotating.

Emsellem et al. (2011) use the λ measures to build on their earlier SAURON project (Emsellem et al. 2007; Cappellari et al. 2007), which introduced this parameterization and used it to classify early-type galaxies as either “fast” (FR) or “slow” (SR) rotators. Division between the two classes in the initial SAURON works was set at $\lambda_{Re} = 0.1$, based on qualitative differences between the rotation curves of systems on either side of this dividing line. SR galaxies had little or no rotation, but also had complex or poorly organized velocity fields. They were inferred to be mildly triaxial. FR galaxies, on the other hand, had well organized rotation patterns aligned with the figure axes of the systems, in addition to the higher amplitude of the rotation over all. They were inferred to be generally oblate, flattened systems. In the larger ATLAS^{3D} sample, Emsellem et al. (2011) were better able to understand the import of projection effects on the observed rotation amplitudes, and revised the FR/SR boundary to be dependent on the apparent figure ellipticity of the galaxies: $\lambda_{Re/2} = 0.265\sqrt{\epsilon_{e/2}}$.

Emsellem et al. (2007), Cappellari et al. (2007), and Emsellem et al. (2011) explored a number of physical differences between the SR and FR sets and concluded that they likely had different formation histories. FR galaxies were inferred to require gaseous dissipation and star formation during the merger of their progenitors, while the SR galaxies would reflect the endpoint of “dry” mergers. As such, the formation of the SR and FR sets is hypothesized to be the same as that for the “core” and “power-law” galaxies, respectively. Emsellem et al. (2007) and Emsellem et al. (2011) did examine the central structure of galaxies for the subset that had *HST* observations, concluding the SR galaxies generally had cores, and FR galaxies generally did not. The λ dividing line between the SR and FR classes was set to a very low value, however, such that the core galaxies were nearly evenly divided between the FR and SR sets (while the much more numerous power-law galaxies in their sample still dominate the FR subsample). Core galaxies that had regular velocity fields that were well-aligned with their projected figure-axes were typically assigned to the FR subset. Again, while a λ -amplitude criterion was used to set the boundary between the two classes, its particular

location was set to select for the *qualitative* differences in the morphologies of the velocity fields.

The high-quality IFU observations of the SAURON and ATLAS^{3D} projects have been profoundly useful in advancing our understanding of early-type galaxies. The motivation of the present work in revisiting the results of Faber et al. (1997) is to illuminate the link between the story told by both kinematics and structure. Because core galaxies fall in both the SR and FR subsets, I am concerned that their role as diagnostics for the formation of early-type galaxies risks being over-looked or minimized. Indeed, this division has been interpreted in the literature to mean that core and power-law galaxies have no kinematic differences. Glass et al. (2011), for example, summarized the work of Emsellem et al. (2007) as showing that there is no clear correspondence between the core and rotational classes, implicitly negating the conclusions of Faber et al. (1997). I argue instead that there is a very deep relationship between the two.

3. The Detection of Cores in Early-Type Galaxies

The classification of the central structure of early-type galaxies is provided by the composite sample of Lauer et al. (2007a), which comprises several *HST* studies of the central structure of early-type galaxies (Lauer et al. 1995; Faber et al. 1997; Quillen et al. 2000; Ravindranath et al. 2001; Rest et al. 2001; Laine et al. 2002; Lauer et al. 2005). The galaxies represented sample the luminosity range from dwarf elliptical galaxies to brightest cluster galaxies. The common thread of these studies is that they all used the Lauer et al. (1995) “Nuker law” to compactly represent the surface photometry distributions of the galaxies. There are 63 galaxies in common to the Cappellari et al. (2011) and Lauer et al. (2007a) sample, which form the sample studied in this paper. The list of galaxies and their parameters are presented in Table 1.

In the Lauer et al. (2007a) sample, a core is defined to be the central region of galaxy interior to which the starlight surface brightness profile takes the form $I(r) \propto r^{-\gamma}$, with $\gamma \leq 0.3$ (Lauer et al. 1995). The transition to a core appears as a “break” in the surface brightness profile, a zone over which the surface brightness profile makes a rapid change in slope from the steep envelope profile to the shallow cusp interior to the core, itself. Power-law galaxies, in contrast, have steep surface brightness-cusps in their centers, with $\gamma \geq 0.5$. The distribution of the two forms of structure is essentially bimodal (Gebhardt et al. 1996; Lauer et al. 2007b; Kormendy et al. 2009). There are a few “intermediate” galaxies with $0.3 < \gamma < 0.5$, but they are rare. Lauer et al. (2007a) showed that they do not fit on the core-parameter relations, thus I include the two examples in the present sample with the

power-law galaxies (indeed, their rotation amplitudes also put them in that set).

Other criteria for identifying cores are possible, but in practice they agree extremely well with the Lauer et al. (1995) formalism. Kormendy (1999), Graham et al. (2003), Ferrarese et al. (2006), and Kormendy et al. (2009) for example, advocated using the centers of Sérsic models fitted to the galaxy envelopes as a reference for determining whether or not a galaxy has a core. In this schema, a core is defined to be a central deficit of light with respect to the Sérsic model, as opposed to “excess light,” which is stellar emission more centrally concentrated than the Sérsic model. In a recent application of this methodology, Dullo & Graham (2012) fitted Sérsic models to the Lauer et al. (2005) surface-brightness profiles, claiming that that Lauer et al. misidentified seven galaxies or 20% of their sample as having cores. A more objective evaluation is that the “Sérsic-reference” and Lauer et al. (1995) criteria appeared to be in conflict about whether cores were present in the galaxies in question; they were not misidentified as cores by Lauer et al. (2007a) through incorrect application of their own criteria. As it happens, however, the concordance between the two methodologies is actually much better than this.

The seven galaxies in question are NGC 1374, 4458, 4473, 4478, 4486B, 5576, and 7213. I show Sérsic fits to three of these, NGC 1374, 4473, and 5576 in Figure 1, where the surface photometry is a blend of the high-resolution profiles of Lauer et al. (2005) at small radii with ground-based photometry at larger radii. The composite profiles extend to radii of $\sim 100''$. Michard & Marchal (1993) provide the ground-profiles for NGC 4473 and 5576 and de Carvalho et al. (1991) provides the profile for NGC 1374.² As can be seen, the Sérsic model fits to the envelopes of these galaxies all show central light deficits or cores in agreement with the classifications of Lauer et al. (2005). Dullo & Graham (2012) in contrast claim that these galaxies have no central deficits, but their fits were done only over the inner regions of the galaxies that were sampled by the *HST* photometry, which covers only the inner $\sim 10\%$ of the present profiles. The Dullo & Graham (2012) Sérsic fits are thus too limited in radius to accurately characterize the envelopes.

Of the remaining galaxies, NGC 4486B actually shows a central deficit with respect to the Dullo & Graham (2012) Sérsic model, but they reject a core classification, claiming that the plateau in the inner light profile is not due to a relative deficit of stars. They do not justify this contradictory statement. Additional guidance comes from the Sérsic fits to profiles derived from large-format imagers provided by Kormendy et al. (2009). These investigators emphasize the need to obtain accurate surface photometry at large radii to

²I selected these three galaxies out of the seven because I had access to complementary ground-based profiles for them.

enable the correct characterization of the envelope. Kormendy et al. (2009) actually do find excess central light in N4486B, as well as for NGC 4458 and N4478. They also provide two Sérsic models for NGC 4473, one of which shows a central light deficit, while the other is fitted to a more restricted envelope domain and shows central excess light. Kormendy et al. (2009) note that NGC 4473 appears to have a core on morphological grounds, but classify it instead as a galaxy with excess light based on considerations of its central kinematics, which indicate the existence of a central counter-rotating stellar disk (Emsellem et al. 2004). Regardless, the physical scale of the NGC 4473 core is normal for its luminosity (Lauer et al. 2007a). In the case of NGC 4458, the Kormendy et al. (2009) Sérsic fit falls below the surface brightness profile for $r < 300$ pc, implying that the central component is an extended system well over an order of magnitude larger than typical nuclear star clusters (see the discussion in Lauer et al. 2007b). The Lauer et al. (2005) core determination is for this inner component, not the envelope component described by the Sérsic model.

I conclude that the concordance between the very different Lauer et al. (1995) and Graham et al. (2003) criteria for the identification of cores is at least at the $\sim 90\%$ level, a conclusion already reached by Kormendy et al. (2009). However, it is clear that the use of Sérsic models to reliably identify cores requires having profiles of large radial extent. Oddly, one relies on the precise form of the galaxy on scales of several kiloparsecs to evaluate the nature of the central structure on scales of a few hundred parsecs or less. Their use may also require subjective choices on the domain over which the models are fitted. The criteria of Lauer et al. (1995), in contrast, are local to the center of the galaxies. In the next section I also show that they are more likely to select galaxies that are rotationally consistent with having cores when the Sérsic models indicate excess central light.

4. Core Galaxies Don’t Rotate Very Much, Unlike Power-Law Galaxies

Figure 2 plots $\lambda_{Re/2}$ as a function of total galaxy luminosity, M_V , with the symbols encoding whether or not the galaxy has core or steep power-law cusp. As can be seen, all core galaxies have $\lambda_{Re/2} < 0.32$, a limit that can be decreased to 0.25, if NGC 3640 is excluded. The median $\lambda_{Re/2}$ for core galaxies is only 0.09, compared to 0.39 for power-law galaxies. The strong segregation of the core and power-law galaxies confirms the conclusion of Faber et al. (1997) that the two forms of central structure correspond to different levels of rotation in the larger bodies of the galaxies.

There are two additional points worth noting. First, as found in Faber et al. (1997), while on average faint galaxies rotate rapidly, and luminous galaxies do not, over the luminosity interval over which core and power-law galaxies coexist, the strength of rotation

remains a strong discriminant between the two types, as is clearly evident in Figure 2 for galaxies with $-22 < M_V < -21$.

The second point is that faint core galaxies with $M_V > -20$ still have low levels of rotation consistent with the luminous core galaxies, rather than power-law galaxies of the same luminosity. These are rare systems with particularly compact cores, thus their connection to core galaxies with $M_V < -21$ might have been questioned. The two core galaxies in the present sample with $M_V > -20$ are NGC 4458 and 4478. It is notable that both galaxies are cases in which the classification of core structure by the Lauer et al. (1995) and Graham et al. (2003) criteria disagreed. Emsellem et al. (2011) indeed flagged NGC 4458 as an anomalous case of a galaxy with a large luminosity excess, but yet that falls into their SR class.

The identification of NGC 4458 and 4478 as core galaxies by the Lauer et al. (1995) criteria, as opposed to their classification as galaxies with central light excesses when referenced to Sérsic models, served as the best predictor of their rotation measures. Of the other galaxies discussed in the previous section, NGC 5576 is classified as an SR by Emsellem et al. (2011), and NGC 4473 is near the top of the $\lambda_{Re/2}$ range occupied by core galaxies, but also is highly elongated (see the discussion below); ATLAS^{3D} has no data on NGC 1374, 4486B, or 7213.

While power-law galaxies do rotate faster than core galaxies, on average, the Figure 2 does show that there are a few power-law galaxies that fall among the core galaxies. This is almost certainly due to projection effects. If the rotation axis of a galaxy falls close to the line of sight, such that the galaxy is viewed largely “face on,” then the amplitude of the rotation observed will be greatly reduced.

To explore this possibility, I have also encoded the ellipticities of the power-law galaxies in Figure 2, using a value of $\epsilon_{e/2} = 0.2$ to separate them into two subsets. All of the power-law galaxies with $\lambda_{Re/2} \leq 0.25$ in fact also have low ellipticities, as compared to the generally-high ellipticities of these galaxies. The suggestion is that these galaxies indeed are face-on to the line of sight. Lauer et al. (2005) also showed that low-ellipticity power-law galaxies were likely to be preferentially face-on. Their Figure 6, reproduced here as Figure 4, shows that inner stellar disks are evident in power-law galaxies only when their inner $\epsilon > 0.25$ — the implication is that all power-law galaxies have disks, a point made initially by Ferrarese et al. (1994), but are not seen below this dividing line because the galaxies are inclined with respect to the line-of-sight.

The relationship between the projected ellipticity of the sample galaxies and their rotation measures is explored further in Figure 3, which directly compares both parameters, a plot

that was heavily emphasized by Emsellem et al. (2011) in their own analysis of the distribution of $\lambda_{Re/2}$ as a function of galaxy properties. Power-law galaxies clearly have preferentially higher ellipticity, while core galaxies are preferentially rounder, in general agreement with the results of Tremblay & Merritt (1996), who explored the relationship between axis ratios and luminosity. At the same time, the handful of core galaxies with high ellipticity still have small $\lambda_{Re/2}$.

The solid line plotted in Figure 3 shows the dividing line, $\lambda_{Re/2} = 0.265\sqrt{\epsilon_{e/2}}$, adopted by Emsellem et al. (2011) to discriminate between their SR and FR classes. While this separation does imply that nearly all SR galaxies are core galaxies, the converse is not true, as roughly half of the core galaxies also fall into the FR class. The dotted line in Figure 3 shows an alternative dividing line of $\lambda_{Re/2} = 0.25$. This frees the FR class of any “contamination” of core galaxies, and leaves only a relatively small number of presumably face-on power-law galaxies in the SR class.

An interesting question is whether or not the cores in the nominal Emsellem et al. (2011) FR versus SR classes reflect important physical differences between the two sets, apart from the regularity and amplitude of their rotational fields. In the present sample, the SR core galaxies correspond to those with $\lambda_{Re/2} \leq 0.10$, or 15 galaxies. It does appear that these galaxies may be preferentially more luminous. The SR core galaxies have a median $M_V = -22.0$, which can be compared to the median $M_V = -21.5$ of the 10 FR core galaxies. Notably, of the nine core galaxies with $M_V < -22$, only one of them, NGC 4649, is a FR galaxy.

An obvious hypothesis is that if cores reflect the endpoint of dry mergers, then the SR galaxies might be systems in which more than one dry merging event has built up the systems, resulting in more thorough erasure of the originally regular rotation patterns of the presumed power-law galaxy progenitors. There is no signature of this in the core structure of the systems, however. If I naively assume that more generations of merging might produce relatively larger cores in the SR versus FR core galaxies, I might expect that residuals in the the $M_V - r_\gamma$ relation of Lauer et al. (2007a), which relates the size of the cores, r_γ , to galaxy luminosity, would be correlated with $\lambda_{Re/2}$. The mean relation in Lauer et al. (2007a) is $r_\gamma \propto L_V^{1.9 \pm 0.03}$. Residuals about this relation are plotted in Figure 5 as a function of $\lambda_{Re/2}$. There is no suggestion of any trend in this graph, thus no indication that there are any interesting differences in at least the core structure of the FR versus SR core galaxies.

The slope of the $M_V - r_\gamma$ relation, itself, is unremarkable. In terms of *mass* of the stars associated with the core and the total stellar mass of the galaxy, the relations in Lauer et al. (2007a) imply $m_\gamma \propto M_*^{1.1 \pm 0.1}$, where m_γ is the “core mass,” and M_* is the stellar mass of the galaxy, itself. The essentially linear proportionality, means that the cores are not growing

faster than their surrounding galaxies over the luminosity interval in which FR core galaxies might be converted to SR core galaxies.

5. Core Morphology and Kinematics Working in Harmony

Faber et al. (1997) divided early-type galaxies into core and power-law galaxies, concluding that the two types had different formation histories. Kormendy & Bender (1996) and Kormendy et al. (2009) divided early-type galaxies into two classes, concluding that the two types had different formation histories. Emsellem et al. (2007) divided early-type galaxies into SR and FR galaxies, concluding that the two types had different formation histories. The description of the SR and FR formation hypotheses sounds more or less the same as those for core and power-law galaxies. My interpretation is that the observations of Emsellem et al. (2007) and Emsellem et al. (2011) not only confirm the conclusion that cores and power-laws have markedly different dynamics, but also show that central structure serves as a sharp way to sort out the two formation families of early-type galaxies common to all of these investigations. I summarize my reasoning as follows:

- Core galaxies have median $\lambda_{Re/2} = 0.09$; Power-law galaxies have median $\lambda_{Re/2} = 0.39$. There is an unambiguous difference in their mean dynamical properties.
- All core galaxies, except one, have $\lambda_{Re/2} \leq 0.25$. All power-law galaxies with $\epsilon_{e/2} > 0.2$ have $\lambda_{Re/2} > 0.25$. The two sets are essentially completely disjoint.
- All power-law galaxies with $\epsilon_{e/2} \leq 0.2$, but for one, have $\lambda_{Re/2} \leq 0.25$. Power-laws with inner ellipticity > 0.25 mostly have inner stellar disks, rounder than 0.25 never do. Slowly rotating power-law galaxies are those simply viewed from an unfavorable angle. Indeed such systems must be observed by chance in large samples, even if all power-law galaxies are intrinsically fast rotators.
- Over the interval $-22 < M_V < -21$, in which core and power-law galaxies coexist, the two subsets remain sharply segregated by their $\lambda_{Re/2}$ values. The two core galaxies with $M_V > -20$ are segregated from power-law galaxies of the same luminosity by their low $\lambda_{Re/2}$ values. Power-law galaxies are typically much fainter than core galaxies, but at all luminosities where the two classes coexist they can be sharply separated by rotation amplitude and projected ellipticity. The differences between core and power-law galaxies are not a trivial consequence of their differing average luminosities.

Over all, the observations are consistent with the hypothesis that core and power-law galaxies have completely disjoint dynamical properties. One can clearly enhance the segre-

gation of core and power-law galaxies in the ATLAS^{3D} sample by simply boosting the SR and FR dividing line to $\lambda_{Re/2} = 0.25$, and perhaps requiring that the FR galaxies also have $\epsilon_{e/2} > 0.2$, as well.³ This, of course, comes with the risk that more truly fast-rotating galaxies will fall into the SR class by virtue of unfavorable projection. A potential solution is to obtain central structure measurements on all galaxies in the ATLAS^{3D} sample with $\epsilon_{e/2} < 0.2$ that presently lack them, such that a sample complete in both structure and kinematics can be constructed. While rotation measures depend on the inclination of the galaxies to the line-of-sight, the structure measures are independent of viewing angle and could be used to sort out which rotation class the rounder galaxies with low $\lambda_{Re/2}$ are most likely to belong to.

The obvious question is does this matter. If one focusses on the properties of galaxies on an individual basis and avoids dividing-lines, as can be done with the parameter plots in Figures 2 or 3, the answer is no. The sense of Kormendy & Bender (1996), Faber et al. (1997), and Emsellem et al. (2007), however, that it does make sense to consider discreet families of early-type galaxies. Sorting objects into classes risks losing important information, but not doing so when they really do appear to correspond to *qualitatively* different origins risks missing the big picture. The problem then is to take care when advancing statements of the sort, “Fast-rotators are this, while slow-rotators are that.” For example, while one could say, “Core galaxies are equally divided between the FR and SR classes” and be technically correct, such a statement completely misses the critical details of picture presented by Figures 2 and 3.

The unique information captured by the SAURON and ATLAS^{3D} projects is the form of the velocity fields. On that side of town, the concern is understanding the physics that turns less-luminous systems with regular velocity fields into the complex and minimally-rotating SR velocity fields. On the side of town that I come from, on the concern has been understanding the physics that turns less-luminous systems that have no cores into luminous galaxies that do. The contested ground is that occupied by galaxies that have cores with regular rotation fields, but of considerably lower-amplitude than those in FR systems lacking cores. Obviously, the creation of cores and the erasure of regular rotation patterns, as more luminous early-type galaxies are built from mergers, are not exactly synchronized. Both processes happen over a range of luminosity, largely but not completely bounded by $-20 > M_V > -22$.

In trying to understand what happens over this range, I come back to the galaxies with

³Kormendy & Bender (2012) have also noted that moving the $\lambda_{Re/2}$ boundary upwards would lead to better separation of core and power-law galaxies.

$M_V > -20$ that I argue have cores. It is true that I cannot know if, say NGC 4458, and 4478 “really” have cores, in the sense that their central structure reflects the same “core-scouring” mechanisms that is hypothesized to set the form of the highly-luminous SR core galaxies with $M_V < -22$ at the end of the line. But at the same time, no-one knows what the full luminosity range of systems that might be generated by “core-scouring” look like, nor what the kinematics of those objects might be, particularly if the initial mergers are of unequal mass, and some amount of gas (as in “damp” mergers) is present in the first steps. If there is a road by which high-luminosity elliptical galaxies are built from the mergers of rapidly-rotating low-luminosity elliptical galaxies, finding its start may be best done by using morphology and kinematics together to find the first galaxies along its path.

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Table 1. Rotation and Core Classifications

Galaxy	Morph	M_V	D (Mpc)	P	$\lambda_{R_e/2}$	$\epsilon_{e/2}$	Ref
N0474	S0	−20.12	29	\	0.21	0.19	6
N0524	S0+	−21.85	25	^	0.33	0.03	4
N0821	E	−21.71	25	^	0.27	0.39	1
N1023	S0-	−20.53	12	\	0.39	0.36	1
N2549	S0	−19.17	13	\	0.52	0.49	2
N2592	E	−20.01	27	\	0.43	0.21	2
N2685	S0+	−19.72	14	\	0.63	0.59	6
N2699	E	−20.25	28	\	0.40	0.20	2
N2778	E	−18.75	24	\	0.43	0.20	1
N2950	S0	−19.73	15	\	0.43	0.24	2
N2974	E	−21.09	22	\	0.66	0.40	1
N3193	E	−21.98	36	∩	0.20	0.14	2
N3377	E	−20.07	11	\	0.52	0.50	1
N3379	E	−21.14	11	∩	0.16	0.10	1
N3384	S0-	−19.93	11	\	0.40	0.06	1
N3414	S0	−20.25	26	\	0.07	0.19	2
N3595	E	−20.96	35	\	0.30	0.38	2
N3599	S0	−19.93	23	\	0.24	0.08	3
N3605	E	−19.61	23	\	0.35	0.35	3
N3607	S0	−21.49	21	∩	0.23	0.19	1
N3608	E	−21.12	23	∩	0.04	0.19	1
N3610	E	−20.96	22	\	0.54	0.40	1
N3613	E	−21.59	30	∩	0.19	0.42	2
N3640	E	−21.96	28	∩	0.32	0.22	1
N3945	S0+	−20.25	19	\	0.56	0.23	1
N4026	S0	−19.79	15	\	0.44	0.44	1
N4143	S0	−19.68	15	\	0.40	0.32	6
N4150	S0	−18.66	14	\	0.34	0.27	4
N4168	E	−21.80	37	∩	0.04	0.13	2
N4261	E	−22.26	33	∩	0.09	0.22	4

Table 1—Continued

Galaxy	Morph	M_V	D (Mpc)	P	$\lambda_{Re/2}$	$\epsilon_{e/2}$	Ref
N4278	E	−21.05	16	\cap	0.20	0.13	1
N4365	E	−22.18	21	\cap	0.09	0.25	1
N4374	E	−22.28	17	\cap	0.02	0.15	4
N4382	S0+	−21.96	17	\cap	0.16	0.20	1
N4387	E	−19.25	17	\backslash	0.32	0.35	3
N4406	E	−22.46	17	\cap	0.05	0.21	1
N4417	S0	−18.94	17	\backslash	0.39	0.42	6
N4434	E	−19.19	17	\backslash	0.20	0.08	3
N4458	E	−19.27	17	\cap	0.08	0.12	1
N4472	E	−22.93	17	\cap	0.08	0.17	1
N4473	E	−21.16	17	\cap	0.25	0.40	1
N4474	S0	−18.42	21	\backslash	0.35	0.47	2
N4478	E	−19.89	17	\cap	0.18	0.17	1
N4486	E	−22.71	17	\cap	0.02	0.04	3
N4494	E	−21.50	17	\backslash	0.21	0.17	1
N4503	S0-	−19.57	17	\backslash	0.47	0.43	2
N4551	E	−19.37	17	\backslash	0.26	0.26	3
N4552	E	−21.65	17	\cap	0.05	0.05	1
N4564	E	−20.26	17	\backslash	0.54	0.48	2
N4621	E	−21.74	17	\backslash	0.29	0.36	1
N4636	E	−21.86	17	\cap	0.04	0.09	4
N4649	E	−22.51	17	\cap	0.13	0.16	1
N4660	E	−20.13	17	\backslash	0.47	0.32	1
N4697	E	−21.49	13	\backslash	0.32	0.45	3
N5198	E	−21.23	38	\cap	0.06	0.15	2
N5308	S0-	−21.26	33	\backslash	0.51	0.64	2
N5557	E	−22.62	52	\cap	0.04	0.16	1
N5576	E	−21.31	27	\cap	0.09	0.31	1
N5813	E	−22.01	28	\cap	0.07	0.17	1
N5838	S0-	−20.51	22	\backslash	0.46	0.30	6

Table 1—Continued

Galaxy	Morph	M_V	D		$\lambda_{Re/2}$	$\epsilon_{e/2}$	Ref
			(Mpc)	P			
N5845	E	−19.98	28	\	0.36	0.24	4
N7332	S0	−19.62	24	\	0.34	0.47	3
N7457	S0-	−18.62	14	\	0.47	0.44	1

Note. — Morphological classifications are from the RC3 (de Vaucouleurs et al. 1991). Distances and total luminosity assume $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The profile type, P, is \ = power-law, \wedge = intermediate form, and \cap = core. The reference column refers to the origin of central structural parameters for the given galaxy as follows: 1) Lauer et al. (2005); 2) Rest et al. (2001); 3) Lauer et al. (1995) or Faber et al. (1997); 4) Quillen et al. (2000); and 5) Ravindranath et al. (2001).

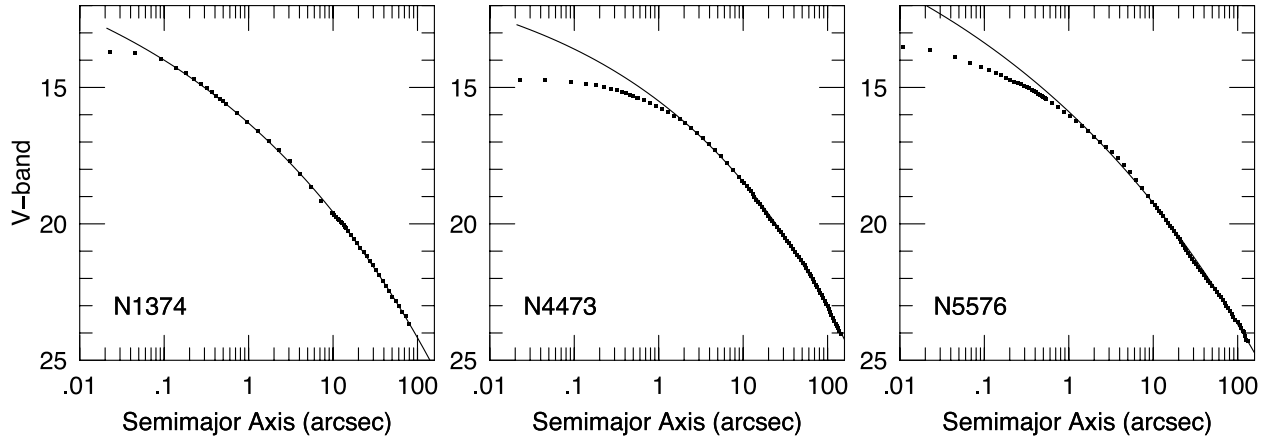


Fig. 1.— Sérsic model fits are shown for three galaxies claimed by Dullo & Graham (2012) *not* to have cores. Central luminosity deficits are clearly evident in all three galaxies, thus they have cores according to their own Graham et al. (2003) criteria, as well as that of Lauer et al. (1995). The surface photometry data combines the *HST* profiles of Lauer et al. (2005) with ground based data, which provide coverage out to $\sim 100''$. The Dullo & Graham (2012) fits were done to only the inner $\sim 10\%$ of the present profiles, and are thus too limited in radius to provide accurate representation of the envelopes.

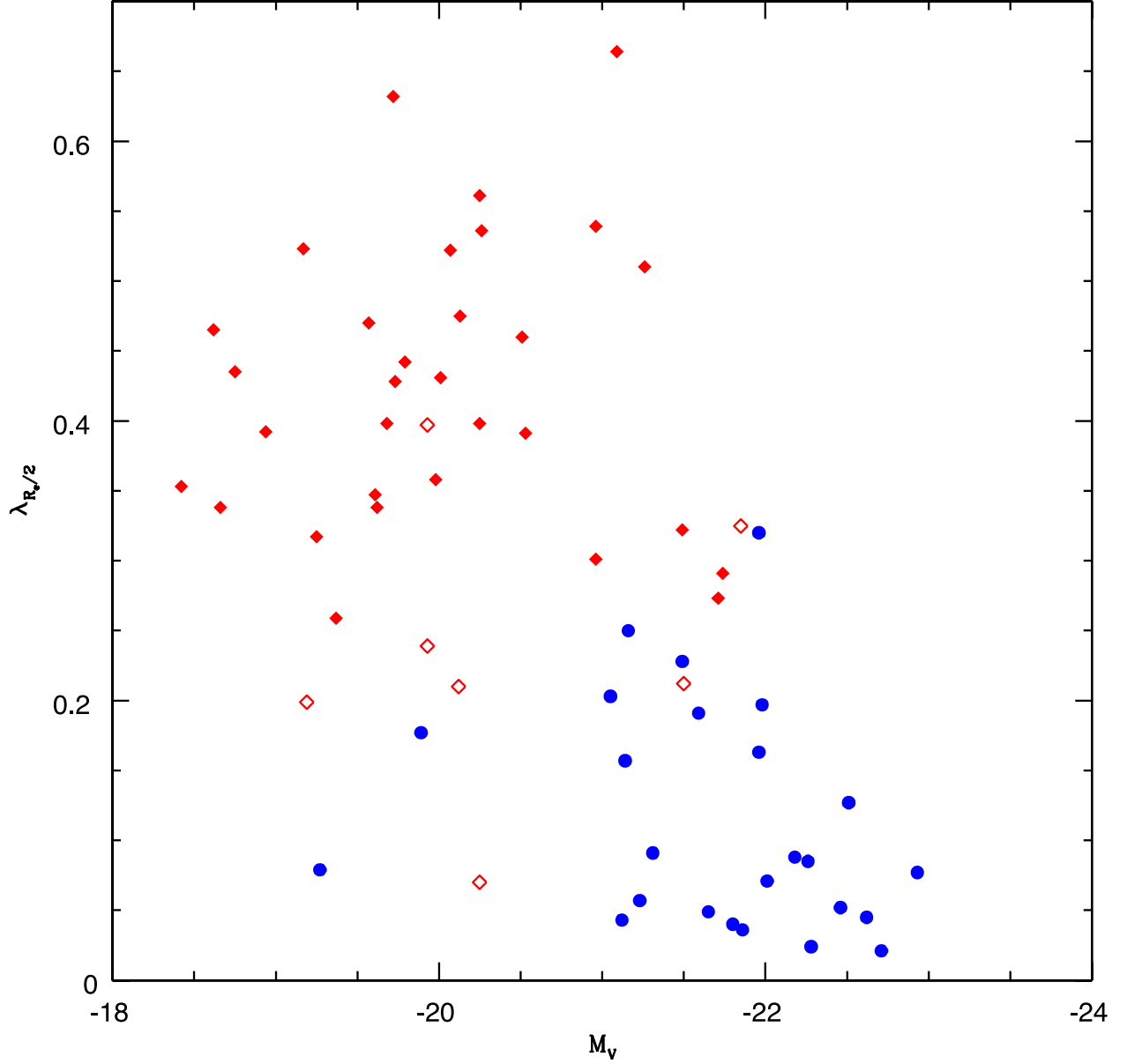


Fig. 2.— Galaxy rotation as measured by the Emsellem et al. (2011) $\lambda_{Re/2}$ parameter is plotted as a function of total luminosity for the galaxies in common between the Emsellem et al. (2011) and Lauer et al. (2007a) samples. Core galaxies are plotted as round-blue symbols, while power-laws are plotted as red-diamonds. Power-law galaxies with $\epsilon_{e/2} \leq 0.2$, which are likely to have low rotation due to projection effects, are further plotted as open diamonds. A clear separation of core and power-galaxies is seen, even in the luminosity range over which the two types coexist.

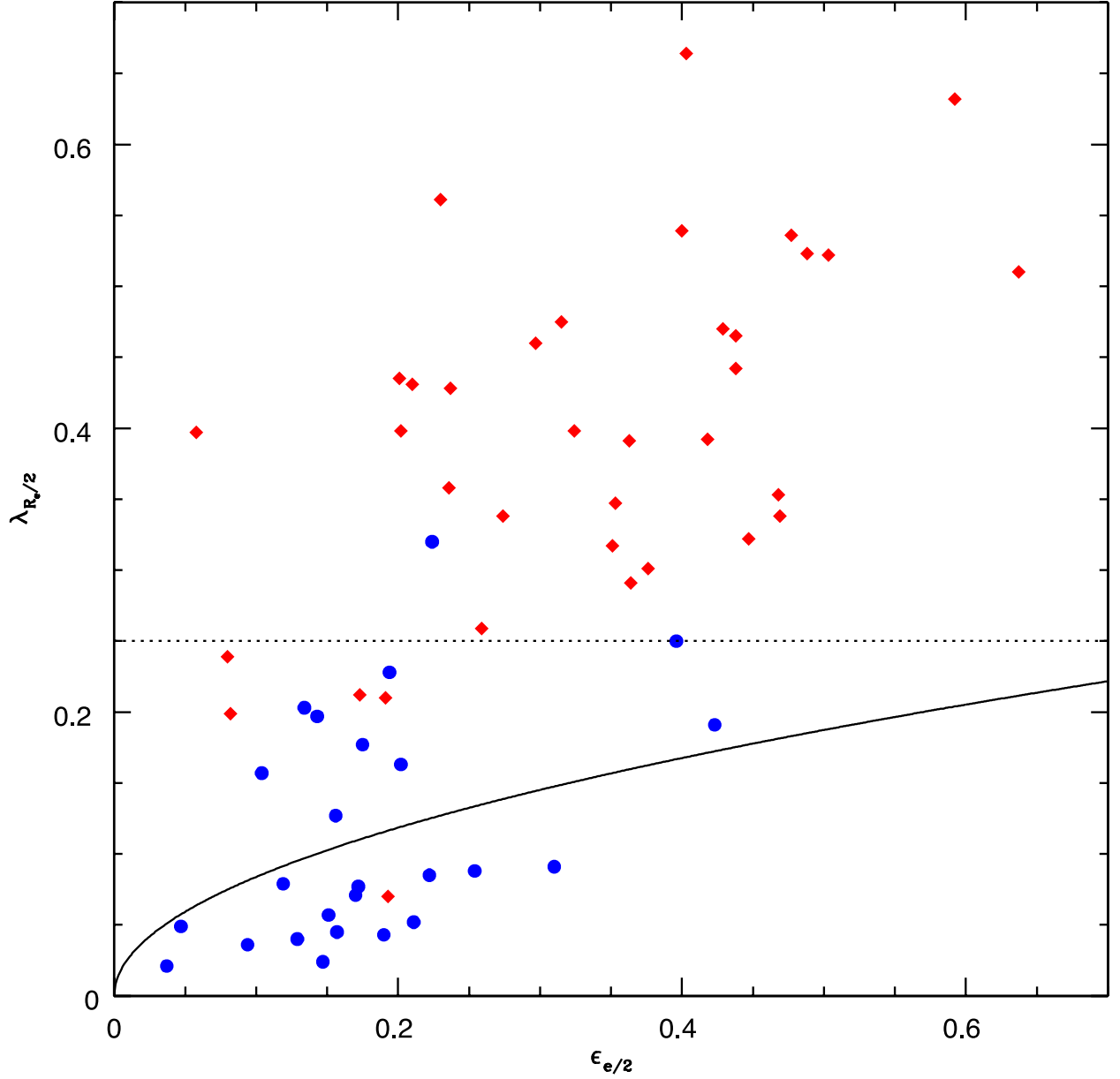


Fig. 3.— Galaxy rotation as measured by the Emsellem et al. (2011) $\lambda_{Re/2}$ parameter is plotted as a function of average ellipticity for the galaxies in common between the Emsellem et al. (2011) and Lauer et al. (2007a) samples. Core galaxies are plotted as round-blue symbols, while power-laws are plotted as red-diamonds. The solid line is the separation between FR and SR galaxies suggested by Emsellem et al. (2011). The dotted line at $\lambda_{Re/2} = 0.25$ neatly separates the core and power-law galaxies into different rotation classes, leaving the core set only contaminated by face-on power-law galaxies.

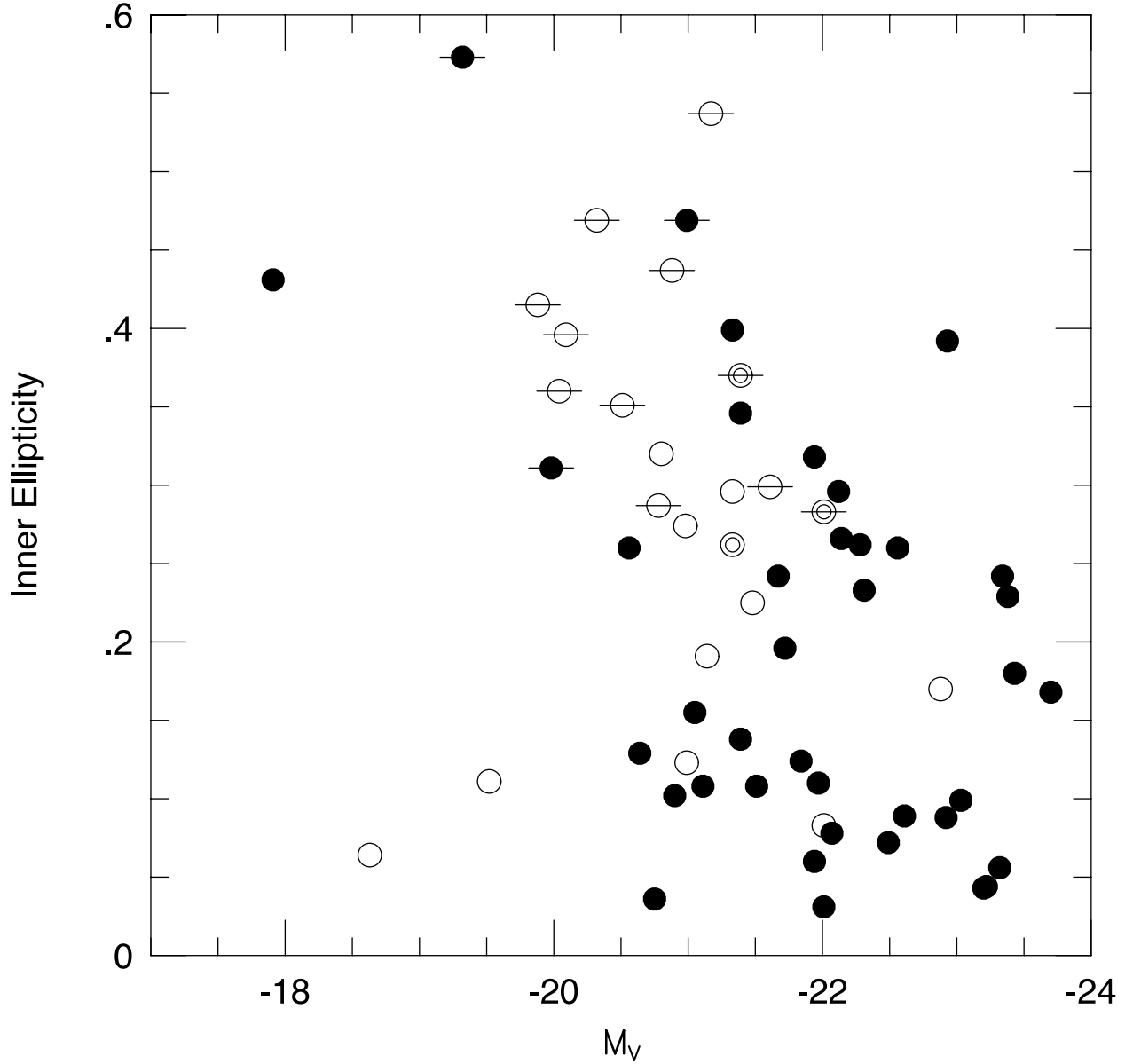


Fig. 4.— Inner luminosity-weighted isophote ellipticity is plotted as a function of total galaxy luminosity, as shown in Figure 6 of Lauer et al. (2005). Solid symbols are core galaxies, open symbols are power-law galaxies, and intermediate galaxies are plotted as double open circles. Galaxies with *inner* stellar disks are indicated with horizontal lines. Nearly all power-law galaxies with $\epsilon \geq 0.3$ have inner disks, implying that they are present in the rounder power-law galaxies, but are not seen due to unfavorable viewing angles. Disks are visible in flattened core and intermediate galaxies fainter than $M_V \approx -21$, suggesting that these are transitional objects. Disks are not seen in bright core galaxies.

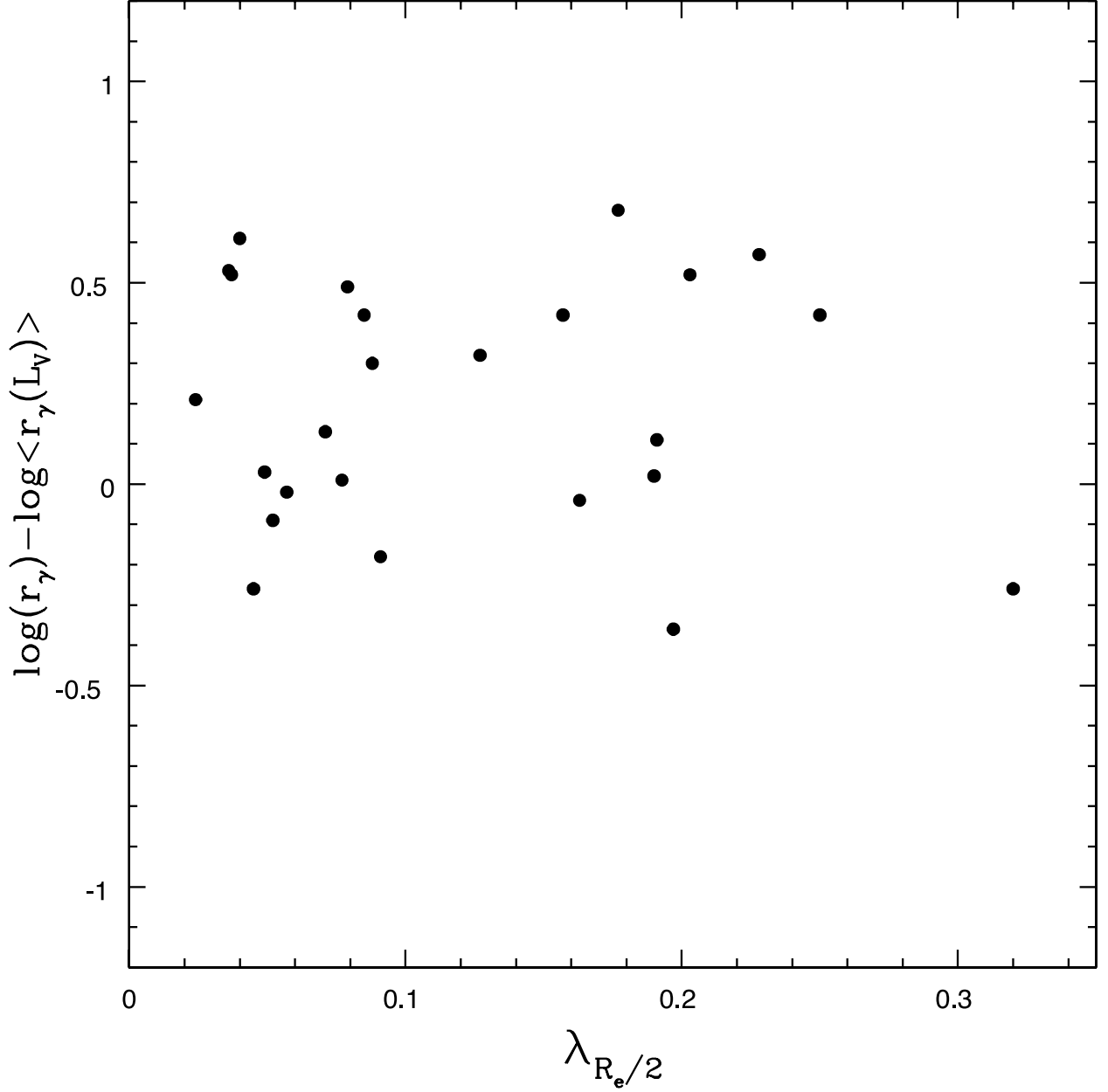


Fig. 5.— Residuals in the core physical scale, r_γ , in the core galaxies from the mean relation between r_γ and galaxy luminosity (equation 14 in Lauer et al. 2007a) are plotted as a function of $\lambda_{Re/2}$ from Emsellem et al. (2011). No trend is evident, so there is no indication that cores in SR core galaxies, that is those with $\lambda_{Re/2} \leq 0.1$, are preferentially larger than those in FR core galaxies.